doi: 10.14355/ijer.2014.0302.01

An Experimental Study on a Density Driven Solar Water Heating System Using Supercritical CO_2 as Working Fluid

Ruchi Shukla[1], K. Sumathy[*2], M. Raisul Islam[3]

Department of Mechanical Engineering, North Dakota State University, Fargo, North Dakota, 58108, U.S.A

[1]Ruchi.Shukla@ndsu.edu; [*2]Sumathy.Krishnan@ndsu.edu; [3]Mohammad.r.Islam@ndsu.edu

Received 17 September 2013; Accepted 10 October 2013; Published 15 May 2014

Abstract

An experimental study was performed to investigate the feasibility and performance of thermosyphon solar water heating (SWH) system using R744 (CO_2) as the working fluid. The uniqueness of the system was the use of carbon dioxide as a working fluid; which is one of the most promising alternative natural refrigerants. For supercritical carbon dioxide, a small change in temperature or pressure can result in a large change in density, especially close to its critical point. At this pseudo critical region, density decreases rapidly with increase in temperature which aids the thermosyphon flow. An experimental setup in which 1.15 m^2 evacuated tube (U-pipe) solar collector acting as a source as well as an evaporator for the refrigerant, was designed and tested based on this principle. Experimental results have shown that it is possible to induce the natural convective flow even during solar-adverse conditions. Although during winter it was not possible to extract any useful heat gain, the system did show some promising results when operated during spring. The time-averaged collector and heat recovery efficiencies for summer were about 58% and 45%, respectively.

Key words

Solar Water Heating; Thermosyphon; Refrigerant; R744; Evacuated Tube Collector; Heat Recovery Efficiency

Introduction

Ecological problems and Potential energy crises in the world have encouraged the development of new sustainable energy options. Solar water heating (SWH) is widely used throughout the world and a large variety of systems are commercially available.

The growing popularity of SWH systems is fueled by their environmentally friendly operations with minimal system maintenance and operation costs as compared to conventional water heating systems. Extensive investigations – have been carried out utilizing various types of collectors, working fluids and storage tanks– both theoretical and experimental studies– to improve the thermal efficiency of the SWH system. Most of the conventional SWH systems utilize water as the heat transfer fluid which cannot be used in solar-adverse regions. This is due to the fact that water-based collectors are susceptible to freezing. Researchers have tried other types of working fluids such as fluorocarbon and hydro-fluorocarbon refrigerants. Although these refrigerants do not damage the ozone layer, many of them do have high greenhouse warming potential (GWP). R134a for instance, has GWP that is 1300 times more than that of CO_2. To overcome the said issue, natural refrigerants such as CO_2, ammonia, and propane may serve as a new alternative.

The selection of a working fluid plays a very significant role in the development of an efficient, cost effective, and environmentally friendly SWH system that can function even when exposed to low ambient conditions. In the proposed study, environmental benign carbon dioxide (CO_2) is selected as the working fluid because of its zero ozone depletion potential (ODP) and negligible GWP. CO_2 is a non-freezing, non-volatile, non-flammable, non-corrosive, and non-toxic natural substance. In addition, it does not need to be recovered or reclaimed when repairing or disposing the equipment, but can be released into the atmosphere with negligible impact. More importantly, the thermodynamic and transport properties of CO_2 are favorable in terms of heat transfer. Table 1 compares the properties of CO_2 with other working fluids. As

mentioned in the Table 1, one property of CO_2 which distinguishes it from other refrigerants is its low critical point (31.1 °C at 7.3 MPa). These properties make CO_2 an ideal working fluid to be used in sub-zero temperatures with low solar radiation.

TABLE 1 ENVIRONMENTAL BENEFITS OF CO_2 [21]

Refrigerant Type	R-134A	R-404A	Ammonia	R-744
Naturally Occurring	No	No	Yes	Yes
ODP	0	0	0	0
GWP	1300	3260	0	1
Critical Point Temp	101.1°C	71.7°C	132.2°C	31.1°C
Critical Point Pressure	4.07 MPa	3.73 MPa	11.3 MPa	7.37 MPa
Triple Point Temp	-103°C	-100°C	-77.8°C	-56.6°C
Triple Point Pressure	40 MPa	2.8 MPa	6.0 MPa	518 MPa
Flammable/Explosive	No	No	Yes	No
Toxic	No	No	Yes	No

Several studies have been initiated utilizing CO_2 as the working fluid. Recently, Zhang et al. have made a detailed study on the collector characteristics with CO_2 as the working fluid and investigated the influence of CO_2 in a U-pipe inserted glass evacuated tube solar collector. It has been reported that the annually-averaged collector efficiency was above 60% in the case of supercritical CO_2 as the working fluid, which is much higher than that of water-based collectors where annually averaged efficiency reached only up to 50%.

Literature shows that most of the CO_2 utilized SWH systems are active systems. In this study, an attempt has been made to design and fabricate a simple thermosyphon solar water heater using supercritical CO_2 as working fluid to investigate for its feasibility in operating in harsh winter regions like those found in North Dakota, USA.

System Description and Thermodynamic Analysis

Figure 1 show the schematic diagram of the CO_2 assisted thermosyphon SWH system being investigated in this study. The system consists of an evacuated tube collector as a heat collecting device, a hot water storage tank with an immersed heat exchanger (HX) as a condenser, a set of valves, high-accuracy sensors, and a data acquisition system.

R744 (CO_2), set in motion by thermosyphon action, is heated in the evacuated tube solar collector. The heating in the solar collector aids a rise in CO_2 temperature, creating a supercritical CO_2 high temperature state. This supercritical CO_2 passes through the outlet header pipe to the storage tank. The high temperature and high pressure CO_2 vapor then rejects the heat to the water through the condenser in the storage tank. Once heat is transferred, low temperature and high pressure CO_2 exit the condenser and move back down to the collector system through the inlet header pipe. One cycle of the operation is thus completed and the system is now ready for the next cycle. Circulation of CO_2 from the collector to the storage tank and vice-versa is affected by buoyancy forces.

As far as thermodynamic properties of carbon dioxide are concerned, the phase envelopes of CO_2 in pressure-enthalpy coordinate is shown in Fig. 2. The figure depicts the thermodynamic properties which clearly illustrates both the critical data and phase envelopes of CO_2 in pressure-enthalpy curve. The heat transfer process in the solar collector leads CO_2 to surpass the critical point resulting in a transcritical cycle. The process curve below the critical point is the subcritical zone and the process curve pertaining to above the critical point refers to the supercritical zone. In this proposed transcritical cycle condition, the change in temperature and pressure of CO_2 are sometimes close to the critical point of CO_2 (T_c = 31.1 °C, P_c = 7.38 MPa). At supercritical pressures, CO_2 thermodynamic and transport properties value vary rapidly with temperature in a region near the pseudo-critical temperature. The pseudo-critical temperature (T_{pc}) refers to a temperature at which the specific heat reaches its maximum, for the given initial input condition.

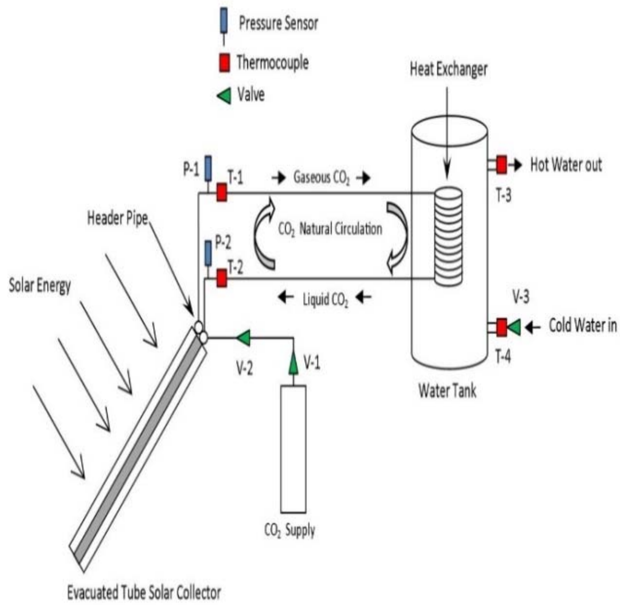


FIG. 1 SCHEMATIC DIAGRAM OF A SIMPLE THERMOSYPHON SWH SYSTEM

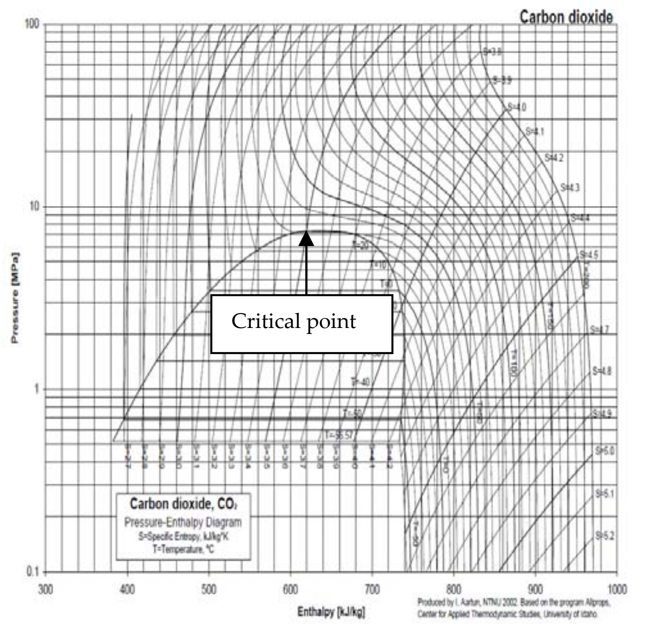


FIG. 2 PRESSURE-ENTHALPY DIAGRAM OF CARBODIOXIDE [30]

Governing Equations

Based on the measured quantities, the following parameters are defined to further analyze the solar water heater:

The useful heat gain (Q_u) of the solar collector is defined as

$$Q_u = F^{'} A_c \left[I_T(\alpha\tau) - U_L(T_f - T_a) \right] \quad (1)$$

In Eq (1), I_T is the global solar radiation input, U_L is the overall heat loss coefficient, T_f is the temperature of the working fluid and $F^{'}$ is the collector efficiency factor which is expressed as

$$F^{'} = \frac{\frac{1}{U_L}}{W\left[\frac{1+\frac{U_L}{C_b}}{U_L[d+(W-d)F]} + \frac{1}{C_b} + \frac{1}{h_f \pi d}\right]} \quad (2)$$

where h_f is the heat transfer coefficient between the fluid and the tube wall. C_b represents the bond conductance, and d is the U-tube diameter. The circumferential distance between U-tubes is given by

$W = P/2$, where P is the perimeter of the cross-sectional area of the tube. The function F is the standard fin efficiency for fin and is expressed as

$$F = \frac{tanh[m(W-d)/2]}{m(W-d)/2} \quad (3)$$

where m is a constant estimated by the following expression:

$$m = \left[\frac{U_L}{\lambda\delta(1+U_L/C_b)}\right]^{1/2} \quad (4)$$

The instantaneous collector efficiency (η_{col}) is defined as the ratio of the useful heat gain (Q_u) delivered to the available solar energy at the solar collector (I_T).

$$\eta_{col} = \frac{Q_u}{I_T A_c} \quad (5)$$

Heat quantity recovered (Q_w) by the storage tank can be expressed in the form of following equation:

$$Q_w = M_w C_p (T_{wo} - T_{wi}) \quad (6)$$

In Eq (6), M_w represents the mass of water within the storage tank, T_{wo} and T_{wi} refer to the water temperatures at the inlet and the outlet of the storage tank, and C_p is the specific heat of water.

Finally, the heat recovery efficiency (η_{RE}) of the system can be evaluated based on the ratio of the heat quantity recovered by the water flow through the heat exchanger (Q_w) to the useful heat gain

$$\eta_{RE} = \frac{Q_w}{Q_u} \quad (7)$$

Experimental Set-up

The main objective of the study is to develop a reliable and a cost effective SWH system, which could operate when exposed to low ambient temperatures and low solar radiation intensity conditions. Accordingly, the main components of a SWH system, such as the collector and the storage tank were appropriately chosen and designed.

With regard to the type of collector, for the desired passive SWH system, both a evacuated tube collector (ETC) and a flat-plate collector (FPC) are more commonly employed. For the given constraint of low ambient and solar insolation conditions, ETC has been chosen in this study. ETC has proven to aid inherent maximum operating temperatures and low heat loss at high temperatures relative to the ambient temperature. In addition, it has a lower absorber plate area to the gross area ratio compared to FPC. The efficiency of a collector is also dictated by the shape of the absorber tube. For instance, Perez et al. confirmed that the glass ETC with a semi-cylindrical shaped absorber tube could absorb approximately 16 % more energy than an ETC with a flat-plate shaped absorber tube. Kim and Seo [31] introduced several potential designs of the absorber tube and investigated the performance of the four different shapes of absorber tubes. The shapes include (i) a finned tube, (ii) an "U-tube" welded inside a circular fin, (iii) an "U-tube" welded on a copper plate. Among the four different designs, an "U-tube" placed inside a circular fin provided the best heat

transfer performance. Therefore, in the present study an U-shaped absorber tube with input and output manifold pipes was designed and was inserted in a glass-in-glass selectively coated ETC, to serve as the heating source.

The design of the storage tank also plays a major role in ensuring the effectiveness of a SWH system. In general, water in the storage tank is heated up either through the 'Direct mode,' or through the 'Indirect mode' of circulation. In 'Direct mode,' water from the storage tank is directly circulated through the collector to affect the heating. On the other hand, in 'Indirect mode,' a different heat transfer fluid is used in the collector, which rejects heat to the water in the storage tank, through heat exchanger. Hence, an 'Indirect mode' of heating is adopted in the present study; accordingly, a helical shaped heat exchanger was designed and immersed in the storage tank. A simple steel tank with an immersed helical shape HX (Fig.1) has been implemented in the present study.

Based on the concepts described above, a prototype of a simple thermosyphon SWH system using supercritical CO_2 as the working fluid was designed, and the details of the outdoor arrangement of the system components are shown in Fig 3. In this optimized design, the supercritical CO_2 flow is induced by natural convection.

In the present experimental set-up, an evacuated tube solar collector of 1.15 m^2 (6 tubes) was used to effectively heat CO_2 to a high-temperature state and eventually to a supercritical state. The collector was oriented to the south at a tilt angle of 45° N (optimized for the latitude of Fargo, ND). The glass evacuated tube solar collector used (Fig.4) in this study has three important features: (i) the outer and inner glass tubes are placed concentrically to provide the vacuum space in between them (ii) the selective absorber coating painted inside the inner tube, and (iii) the copper U-pipe being placed inside the inner glass tube with a connected fin. The ETC used in the study has shown to have a high solar absorbance ranging between 0.90-0.92 and possess a low emissivity value of 0.19. Heat gained by the inner glass tube wall of the ETC, is transferred to the working fluid. Based on the pressure rating (12 MPa) and operational temperature range (-15 °C to 90 °C), the dimensions of the copper tubing in the "U-tubes" have an outer diameter of 6.35 mm and an inner diameter of 3.17 mm. The tubing in the header has an outer diameter of 9.52 mm and an inner diameter of 6.35 mm. Further details of the collector been summarized are listed in Table 2. ETC's with stainless steel "U-tubes" are generally used for designing such a high pressure system. However, in this study copper was used, to effect higher temperatures, when exposed to solar adverse conditions.

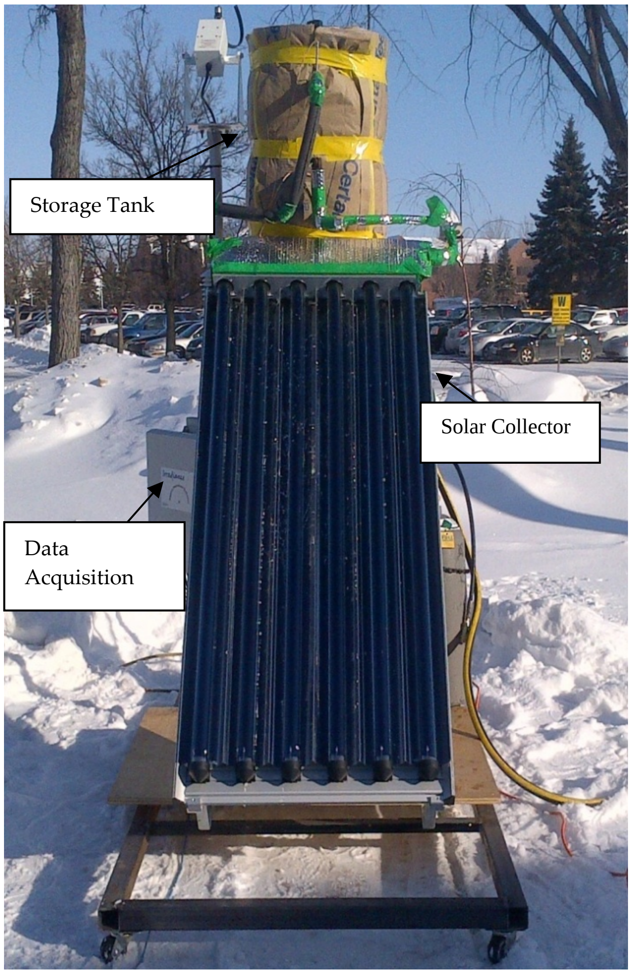


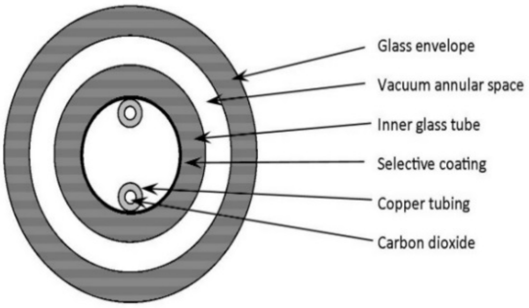
FIG. 3 FRONT VIEW OF SWH SYSTEM

The volume of the storage tank used in the system depends largely on the collector area. Therefore, a 60 Liter storage steel tank was chosen for the given collector area (1.15 m^2). The heat output from the ETC is delivered to the insulated 60 L capacity storage tank through an immersed helical shaped copper coil heat exchanger made from 9 turns of the "header" copper tubing, which has a surface area of 0.04 m^2. To reduce heat losses, fiber glass insulation is applied on all the carbon dioxide and the water loop.

The evacuated tube collector and storage tank were integrated together to form a closed-loop. Three valves were utilized to control the systems operation. As shown in Fig. 1, Valve 1 (vent valve) helps to relieve the pressure, which facilitates the disconnection of the CO_2 reservoir/supply. Valve 2, is a high pressure

needle valve which was installed at the inlet of the solar collector to charge the system from the CO_2 supply. To control the flow of water, valve 3, an automatic valve, was integrated to the inlet of the storage tank.

(a)



(b)

FIG. 4 EVACUATED TUBE SOLAR COLLECTOR (a) FRONTVIEW (b) CROSS-SECTIONAL VIEW [30]

TABLE 2 THE PARAMETERS FOR THE GLASS EVACUATED TUBE SOLAR COLLECTOR

Material	Parameters	Value
Absorbing coating	Absorptivity	0.92
	Emissivity	0.19
Outer glass tube	Outer diameter (m)	0.04
	Inner diameter (m)	0.03
	Thickness (m)	0.0015
Air layer	Conductivity (W/mK)	1.2
	Thickness (m)	0.001
	Conductivity (W/mK)	0.03
Copper fin	Thickness (m)	0.0006
	Conductivity (W/mK)	307
U-tube	Outer diameter (m)	0.0063
	inner diameter (m)	0.0031
	Thickness (m)	0.015

Collector surface temperature, storage water tank temperature, and temperature of CO_2 at various locations of the system were measured, using J-type thermocouples with an accuracy of ±0.2°C as quoted on the J-type thermocouple wire specification sheet. The high CO_2 pressures at various locations of the systems were measured, using pressure transmitters with an accuracy of ±0.25%. A solarimeter was used to measure the intensity of the global solar radiation incident on the collector surface. The above measuring processes were controlled and monitored by personal computer-based data acquisition software. The data was recorded at 5 min intervals in a data logger, which was used for the data analysis.

The proposed design (Fig. 3) provides an environmentally-friendly alternative for heating needs and can be easily mounted anywhere on a wall or roof. This design serves as a promising potential to supply hot water in solar-adverse regions such as Fargo, North Dakota. The system can be suitable for a variety of residents, especially for those living in apartment blocks with south-faced outside walls and windows. The other components of the system can be combined in a compact way and installed inside a building to avoid adverse weather related issues.

Results and Discussions

The feasibility of the proposed system to perform under adverse weather conditions was studied during the period Feb-May 2013. The instantaneous global solar radiation at the collector, the CO_2 fluid pressure at the inlet and the outlet of the collector, CO_2 fluid temperature at the inlet and the outlet of the heat exchanger, as well as the temperature of the storage tank were measured. The collected data was used to determine the performance factors such as the collector inlet/outlet temperature difference, useful energy gain, collector efficiency and the heat recovery efficiency of the system.

The experimental set-up was tested in Fargo, North Dakota, and the data collected on May 17, 2013, had been analyzed and presented in this paper. The system was set in operation from 07:30 to 17:30 hours. Figure 5 clearly shows that during the test day, through the morning until noon had clear sky day and rest of the day it was cloudy. The time-averaged ambient temperature and solar radiation values were 20 °C and 396 W/m^2, respectively.

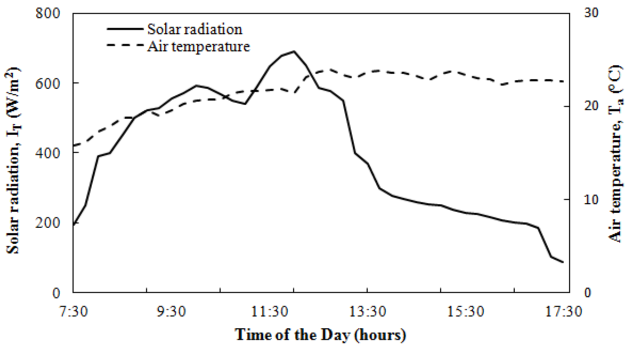


FIG. 5 VARIATION OF SOLAR RADIATION AND AMBIENT TEMPERATURE VS TIME OF DAY

Thermocouples were used to monitor the temperature of CO_2 refrigerant. Initially, the system was charged with CO_2 until the initial pressure of 5.5 MPa was achieved, it was exposed to sunlight. During the initial hours of exposure, a steady rise in CO_2 temperature and pressure was noticed. Measured values of CO_2 temperature both at the inlet and the outlet of the collector are plotted in Fig. 6. During the test period, the CO_2 temperature at the collector outlet varied from 17 °C to 80 °C. At such high temperatures, supercritical CO_2 can serve as a useful solar thermal source for hot water supply in cold regions. Literature shows that, it is difficult to achieve such temperature gain, with conventional flat plate collectors. This improved design has successfully generated approximately a 60 °C rise in the CO_2 temperature. It is due to the fact that, when CO_2 temperature is close to its supercritical state, even a small change in pressure and temperature results in dynamic changes in its thermo-physical properties.

Figure 6 also shows the variation in pressure of CO_2, both at inlet and outlet conditions of the collector. During test hours, it was noticed that not only CO_2 temperature, but also CO_2 pressure in the collector, was influenced by solar radiation. The changes in the CO_2 pressure at the collector inlet and outlet have similar trends. It could be seen that the CO_2 pressure at the solar collector rises from 5.5 MPa to 9.5 MPa within 07:30 to 13:30 hours. Even during cloudy periods, though there was a reduction in CO_2 pressure, it stabilized to about 7.5 MPa, which is above the critical point of CO_2 (7.3 MPa). Beyond 15:00 hours with further decrease in temperature and pressure, the CO_2 fluid enters a subcritical zone.

The relationship between temperature, pressure, enthalpy, and entropy are shown in pressure-enthalpy diagram in Figure 7. In this figure, the critical point "C.P." is located at the peak of the vapor dome. As stated earlier, CO_2 is a supercritical fluid at temperatures above 31.1 °C and pressure above 7.3 MPa. The fluid states of CO_2, both at the inlet and outlet of the collector, are shown in the figure. It can be seen that during the entire test period, at the inlet of the collector, the CO_2 is in liquid state. On the other hand, at the collector outlet, CO_2, initially is in liquid phase, and then enters into supercritical state. However, beyond the 15:00 hours CO_2 enters the mixed zone due to low solar radiation input.

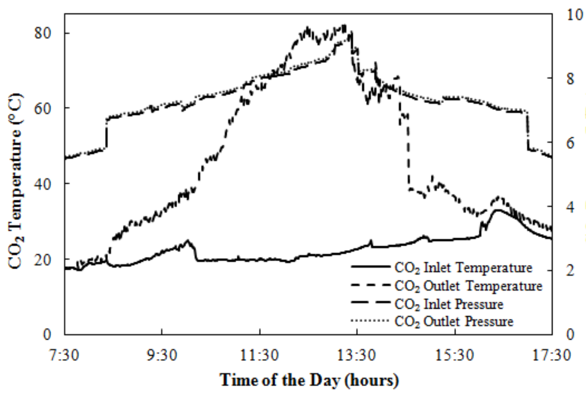


FIG. 6 VARIATION OF CO2 TEMPERATURE AND PRESSURE VS TIME OF DAY

As seen in Figure 8, during the test day the initial water temperature was at 15 °C. The gain in solar insolation and an increase in CO_2 temperature are reflected in terms of rise in storage rank water temperature. The system attained a maximum temperature of about 38 °C. The improved design generated a 23 °C rise in storage tank temperature, which is in line with the previous study. However, it should be pointed out that, the expected storage tank water temperature is lower compared to the gain in the CO_2 temperature at the outlet of the collector. Several factors such as the insulation, condenser design, and wind effect might have contributed to such differences. Given the severe Fargo winter weather conditions, the designed heat exchanger is not an optimal one. Along with the heat exchanger design, choice of the insulation also plays a major role in ensuring the better increase in the storage tank temperature by avoiding the heat losses. Generally, water heaters are available with insulation rating ranging R-6 to R-24. For the proposed design, fiber glass insulation (R-13 of 3.5 inch thickness) was used to minimize the heat losses. As seen in the Figure. 8, beyond 13:30 hours the storage tank temperature was continuously dropping from 38 °C (13:30 hours) to 32 °C (17:30 hours). This 6 °C drop reflects the fact that fiber glass insulation used in the study could not meet the requirement for Fargo

weather conditions. Hence, it is recommended to use higher R–value rating insulation (minimum of R-30) along with vapor barrier techniques when exposed to such weather conditions. In addition to insulation problems, wind speed also had a detrimental effect on tank temperature as the average wind speed on the test day was around 4.1 m/s. This was relatively high compared to the average wind speeds on a typical summer day in Fargo (2.9 m/s). Therefore, to attain higher heat recovery efficiency, storage tank and condenser design must be optimized, in addition to the utilization of an appropriate insulation.

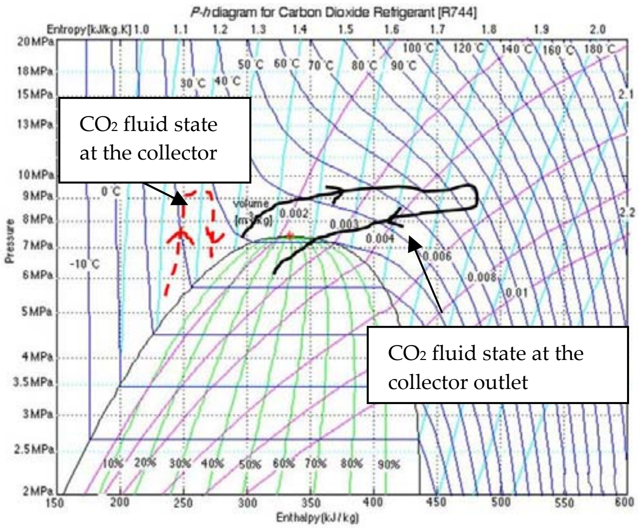


FIG. 7 CO2 PRESSURE-ENTHALPY DIAGRAM SHOWING CO2 FLUID STATES DURING THE TEST PERIOD

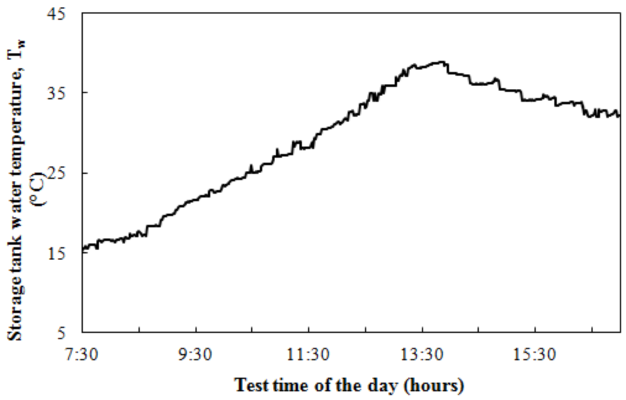


FIG.8 VARIATION OF STORAGE TANK WATER TEMPERATURE VS TIME OF DAY

The above discussed factors had an influence on the collector useful heat gain (Q_u) as well as the heat recovered (Q_w) by the water in the storage tank (Fig. 9). As seen in the figure, the solid line indicates the useful heat gain by the collector (Q_u), the dash line indicates the recovered heat by the water in the storage tank. With increase in solar insolation levels, the collector heat gain also steadily increased accordingly and attained a maximum value of 600 W. As mentioned earlier, due to the cloudy effect beyond 13:30 hours, the collector heat gain reduced to a minimum of 160 W at 17:30 hours. The values of the heat quantity recovered oscillate greatly and the time-averaged heat quantity recovered is evaluated to be about 150 W. Based on the data obtained, the time-averaged collector efficiency (η_{col}) and heat recovery efficiency (η_{RE}) is calculated around 58% and 45% respectively, and are shown in Fig. 10. Although, the results obtained pertain to one day measured data, other parametric studies carried out during similar weather conditions showed the similar time-averaged collector efficiencies of about 55-65%.

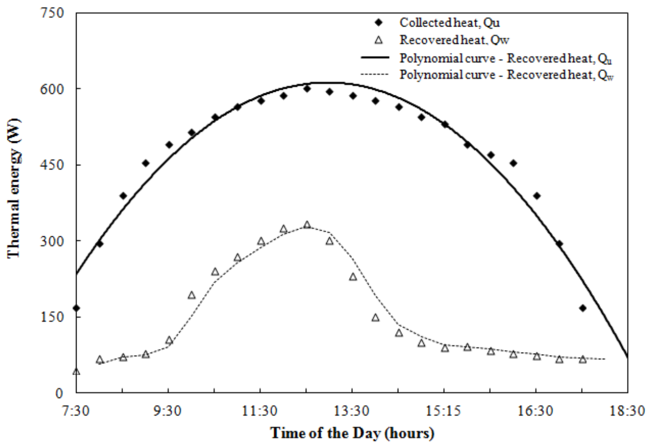


FIG. 9 VARIATION OF COLLECTOR USEFUL HEAT GAIN AND RECOVERED HEAT QUANTITY VS TIME OF THE DAY

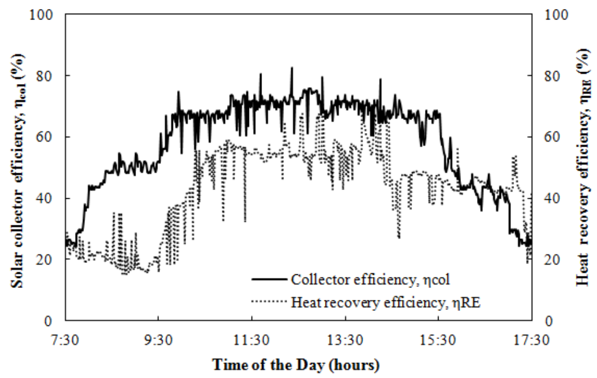


FIG. 10 VARIATION OF COLLECTOR EFFIECNCY AND HEAT RECOVERY EFFICIENCY VS TIME OF DAY

Figure 11 shows the overall performance of the CO_2 assisted water heating system on typical days with clear sunshine, during different months (Feb-May, 2013). It can be seen that, in late winter (February), although CO_2 is shown to have increase in temperature, it cannot effectively heat the water in the storage tank. This is because, when exposed to extreme low ambient temperatures (around -10 °C), the fiber glass insulation

used for the storage tank could not effectively prevent the heat losses. Based on the test data collected, it is suggested that thermosphoning system is not suitable in solar adverse regions. It should be noted, the preliminary results have proven that, even in extreme winter conditions, it is possible to affect CO_2 heating; the energy gain can be effectively harnessed for water heating purposes through heat pump technique. However, as shown in Fig. 11, during spring season (April-May), the system did show some promising results.

Results obtained from the present study are encouraging as it signifies that the environmental benign refrigerant CO_2 (R744), can serve as an efficient working fluid compared to water when exposed to solar adverse conditions. There are several characteristics of CO_2 that contribute to the high efficiency of CO_2-based collector compared to traditional collectors using water as working fluid. The collector efficiency could further be improved by implementing heat transfer through forced convection than natural convention.

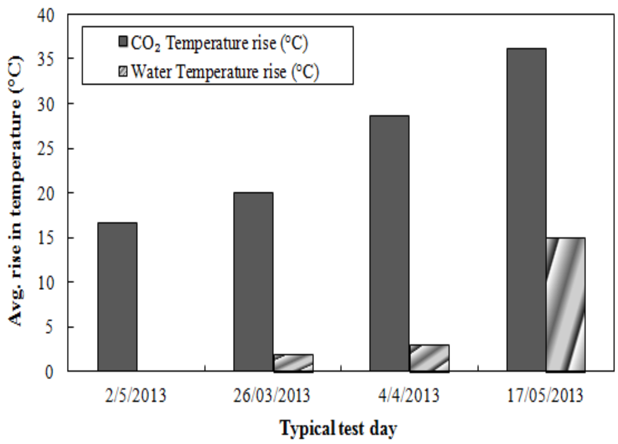


FIG. 11 CO2 TEMPERATURE AND THE CORRESPONDENCE AVERAGE RISE IN TANK TEMPERATURE FOR TYPICAL DAYS OF DIFFERENT MONTH

Conclusion

A CO_2 assisted water heating system using U-tube evacuated tube collector has been investigated for Fargo, ND, weather conditions. The thermal performance of the system is determined based on the measured collector temperature and water temperature in the storage tank, under different weather conditions. The results indicate that, the time - averaged collector efficiency (η_{col}) and heat recovery efficiency (η_{RE}) are calculated around 58% and 45% respectively. Experiments have shown the potential of using CO_2 as the working fluid in SWH systems when need to be operated in solar adverse regions. However, thermosyphon based SWH system is not recommended for winter conditions. A suggestion for further studies is to investigate the heat pump based CO_2 driven SWH system when subjected to solar adverse condition (very low T_a and wind chill temperature).

Nomenclature

A_c	the outer surface area of absorber tube, (m^2)
C_b	bond conductance, (W m^{-1} K^{-1})
d	diameter of the U-tube, (m)
F	fin efficiency of straight fin
F'	collector efficiency factor
h_f	the heat transfer coefficient between the fluid and the U-tube wall, (Wm^{-1} K)
Q_u	useful energy gain, (W)
Q_w	heat quantity recovered, (W)
T_a	ambient temperature, (K)
T_f	mean temperature of the working fluid, (K)
U_L	overall loss coefficient, (W m^{-2} K^{-1})
W	the circumferential distance between the U-tubes, (m)
I_T	total solar radiation
M_w	mass of water in storage tank, (kg)
C_p	specific heat of water (kJ kg^{-1} K^{-1})

Greek

δ	the thickness of the copper fin, m
η	solar collector efficiency
λ	conductivity of copper fin, W/(m K)
α	Absorptance

Subscripts

col	collector
RE	heat recovery
w	water
i	inlet
f	fluid
u	useful
o	outlet

ACKNOWLEDGEMENT

This research was partly supported by a grant from the Pakistan-US Science and Technology Cooperation Program, US Department of State (jointly administered by the National Academics and Higher Education Commission of Pakistan).

REFERENCES

A. Houri. Solar water heating in Lebanon: current status and future prospects. Renewable Energy. 31, 663-675 (2006).

A.A. Karaghouli and W.E.Alnaser. Experimental study on thermosyphon solar water heater in Bahrain. Renewable Energy. 24, 389-396 (2001).

B. Norton and S.D. Pobert. Natural circulation solar energy simulated systems for heating water. Appl. Energy. 11, 167-173 (1982).

B.J. Huang. Similarity theory of solar water heater with natural circulation. Solar Energy. 25, 105-16 (1980).

D.A.G. Redpath, P.C. Eames, S.N.G. Lo and P.W. Griffiths. Experimental investigation of natural convection heat exchange within a physical model of the manifold chamber of a thermosyphon heat-pipe evacuated tube solar water heater. Solar Energy. 83, 988-97 (2009).

D.A.G. Redpath, S.N.G. Lo and P.C. Eames. Experimental investigation and optimisation study of a direct expansion thermosyphon heat-pipe evacuated tube solar water heater subjected to a northern maritme climate. International Journal of Ambient Energy. 31, 91-100 (2011).

D.J. Close. The performance of solar water heaters with natural circulation. Solar Energy.6:33-40 (1962).

G .Grossman, A. Shitzer and Y. Zvirin. Heat transfer analysis of a flat-plate solar energy collector. Solar Energy. 19, 493-502 (1977).

G. Morrison, T. Anderson and Behnia. Seasonal performance rating of heat pump water heaters. Solar Energy. 76, 147-152.

G.L. Morrison and D.B.J. Ranatunga. Thermosyphon circulation in solar collectors. Solar Energy. 24, 19-198 (1980).

H. Arif and K. Yildiz. A review of heat pump water heating systems. Renewable and Sustainable Energy Reviews. 13, 1211-1229 (2009).

H. Yamaguchi, N.Sawada, H.Suzuki, H.Ueda, and X.R. Zhang. Preliminary Study on a solar water heater using supercritical Carbon dioxide as working fluid. Journal of Solar Energy Engineering. 132 (2010).

I. Budihardjo, G.L. Morrison. Performance of water-in-glass evacuated tube solar water heaters. Solar Energy. 83, 49-56 (2009).

J. Huang, S. Pu, W. Gao and Y. Que. Experimental investigation on thermal performance of thermosyphon flat-plate solar water heater with a mantle heat exchanger. Energy. 35, 3563-8 (2010).

K. C. Ng, C. Yap, T.H. Khor. Outdoor testing of evacuated-tube heat-pipe solar collectors, Proceedings of the Institution of Mechanical Engineers. 214, 23-30 (2000).

K. Ochsner. Carbon dioxide heat pipe in conjugation with a ground source heat pump (GSHP). Applied Thermal Engineering 28, 2077-2082.

K.S. Ong. An improved computer program for the thermal performance of a solar water heater. Solar Energy. 18, 183-91 (1976).

L. Ma, Z. Lu, J. Zhang and R. Liang. Thermal performance analysis of the glass evacuated tube solar collector with U-tube, Building and Environment. 45, 1959–67 (2010).

M.F.Young and J.B. Bergguam. Performance charactestics of a thermosyphon solar domestic hot water system. ASME J. Solar Energy Engng. 103, 193-199 (1981).

M.H. Kim, J. Pettersen and C.W. Bullard. Fundamental process and system design issues in CO_2 vapor compression systems. Progress in Energy and Combustion Science. 30, 119-174 (2004).

M.S. Sodha and G.N. Tiwari. Analysis of natural circulation solar water heating systems. Energy Conversion and Management. 21, 283-8 (1981).

P.A.Hobson and B.Norton. A design nomogram for direct thermosyphon solar-energy water heaters. Solar Energy. 43, 85-95 (1989).

R. Perez, R. Seals, J. Anderson and D. Menicucci. Calculating Solar Radiation Received by Tubular Collectors. Journal of Solar Energy Engineering. 117, 341-4 (1995).

R. Riebere. Naturally circulating probes and collectors for grounded-coupled heat pumps. International Journal of Refrigeration. 28, 1308-1315 (2005).

R. Shukla, K. Sumathy, P. Erickson, J. Gong. Recent Advances in the Solar Water Heating Systems: A Review. Renewable and Sustainable Energy Reviews. 19, 173–190 (2013).

S. Jaisankar, T.K. Radhakrishnan and K.N. Sheeba. Experimental studies on heat transfer and friction factor characteristics of forced circulation solar water heater system fitted with helical twisted tapes. Solar Energy. 83, 1943-52 (2009).

S. Jaisankar, T.K. Radhakrishnan, K.N. Sheeba and S. Suresh. Experimental investigation of heat transfer and friction factor characteristics of thermosyphon solar water heater system fitted with spacer at the trailing edge of Left–Right twisted tapes. Energy Conversion and Management.

50, 2638-49 (2009).

S.J. Jeong and K.S.Lee. An experimental study of a carbon dioxide-filled thermosyphon for acquition of low-temperature waste enrgy. Int. J. Energy Res. 34, 454-461 (2010).

X.R. Zhang and H. Yamaguchi. An experimental study on evacuated tube solar collector using supercritical CO_2. Applied Thermal Engineering. 28, 1225-33 (2008).

X.R. Zhang, H. Yamaguchi, D. Uneno, K. Fujima, M. Enomoto and N. Sawada. Analysis of a novel solar-energy-powered Rankine cycle for combined power and heat generation using supercritical carbon dioxide. Renewable Energy. 31,1839-1854 (2006).

X.R. Zhang, H. Yamaguchi, K. Fujima, M. Enomoto, and N. Sawada. Theoretical analysis of a thermodynamic cycle for power and heat production using supercritical carbon dioxide. Energy. 32, 591-599 (2007).

Y. Kim and T. Seo. Thermal performances comparisons of the glass evacuated tube solar collectors with shapes of absorber tube. Renewable Energy. 32, 772-95 (2007).

http://en.wikipedia.org/wiki/Hot water_storage_tank